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Estimation of materials-induced CO_2 emission from road construction in Korea

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ABSTRACT

The first attempt has been made in Korea to quantify the carbon dioxide (CO_2) emitted from the consumption of main and basic materials for road, bridge and tunnel constructions. These materials-induced CO_2 emissions were estimate using the amount of materials consumed and corresponding CO_2 emission factors. A simple linear relation was developed between unit price and emission factor for some of basic materials whose emission factors were not available. To demonstrate overall and unit emissions, twelve expressway sections constructed between 2006 and 2007 have been selected and consumed materials have been identified. The unit emissions were then utilized to estimate the total emissions that might have been released from all types of roads (expressways, national highways and local roads) up to the year 2007. Also, the effects of number of traffic lanes and bridge types on the CO_2 emissions were briefly discussed. Finally, average annual CO_2 emissions were predicted based on road construction plans from 2009 to 2020. One of the results suggested that bridges should induce the largest emissions per meter (120.1 tCO_2/m), followed by tunnels (29.6 tCO_2/m) and road-only sections (7.5 tCO_2/m) due to the consumption of main construction materials.

Contents

1. Introduction

Since the beginning of the industrial revolution, the burning of fossil fuels has contributed to the increase in greenhouse gases (GHGs) in the Earth's atmosphere. The GHGs produced by human

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activities mainly come from combustion of wood, coal, oil, and natural gas. Excessive GHGs cause the global warming phenomenon leading to climatic changes and natural disasters around the globe. There are many ongoing political and technological approaches taken to curb the GHG growths. In order for these efforts to be successful, a thorough understanding about the GHG shares is fundamental. The GHG shares are normally defined for several sectors, such as energy, transport, industrial process, agriculture, and waste [1–4]. In the republic of Korea (hereinafter Korea), the transport sector is known to account for about 17% of total national GHGs and has been considered as the second largest GHG contributor since 1970. GHGs in this sector have been directly affected by road vehicles (cars) that need to burn lots of carbonaceous fuels to run [5]. In addition, the number of road vehicles keeps increasing, making this trend worse. According to the vehicle registration records by Korea Ministry of Land, Transportation and Maritime (MLTM), Korea had 4248,000 road vehicles registered in 1991, but they reached over 18 million in 2011 and are expected to exceed 20 million in 2014 [6]. To accommodate this trend, new roads should be built in many busy areas and at the same time old roads should be maintained and rehabilitated properly. Although most of investigations into GHGs emitted from roads have focused and are still focusing on the characteristics of traffic (e.g., traffic volume, pattern, speed, etc.) [7–12], some attempts have been made to understand the GHGs generated from either machineries or materials utilized for road constructions. Avetisyan et al. [13] and Kim et al. [14] evaluated the GHGs resulting from construction machineries; Hanson et al. [15] and Shi et al. [16] investigated the effect of some construction materials on GHGs. A few studies also have been carried out to characterize the GHGs due to the construction and maintenance of roads [17–19].

Observing the lifecycle of roads depicted in Fig. 1, it is clear that many sources of energy are being consumed in various phases of roads, causing lots of GHG emissions.

To calculate the GHGs emitted during the LifeCycle of roads, the so-called LifeCycle inventory (LCI) database of energy should be developed in each phase. This database provides individual gate-to-gate, cradle-to-gate and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in each country [20]. Recently, the first version of LCI database has been developed by the Korea Ministry of Knowledge Economy (MKE) and the Korea Ministry of Environment (ME), but most of construction materials were not covered by the database.

The purpose of this study was to quantify the carbon dioxide (CO_2), one of primary GHGs, due to the consumption of materials for the construction of roads, bridges, and tunnels. Although the CO_2 emissions (hereinafter the emissions) can be either from materials or from construction machineries, this study has focused on the CO_2 emissions from materials (i.e., materials-induced emissions). The emissions from materials for the construction of tunnels and bridges were separately calculated to compare to those from materials used for road-only sections. To demonstrate overall and unit emissions, twelve expressway sections constructed between 2006 and 2007 have been selected from the construction reports published by Korea Expressway Corporation (KEC). The unit emissions were then utilized to estimate the total emissions that might have been released from all types of roads (expressways, national highways and local roads) up to the year 2007. In addition, the effects of number of traffic lanes and bridge types on the emissions were studied, and average annual emissions were predicted based on road construction plans from 2009 to 2020. This is one of pilot studies that present the current status of the materials-induced emissions as a result of road constructions. Some results could be strategically utilized for the minimization of the emissions, ultimately leading to the realization of green road construction [21].

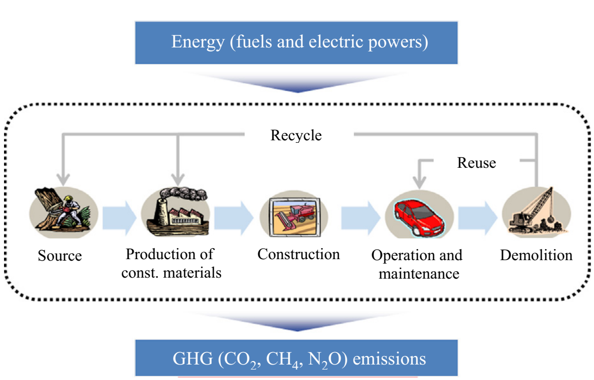

Fig. 1. Lifecycle of road and GHGs.

2. Methodology

2.1. Expressway routes

In this study, twelve four-lane road sections were chosen from five expressway routes constructed across the country from 2006 to 2007 to understand and quantify the materials-induced emissions. This choice was made since the reliable data were available for those sections and years that best represent an up-to-date road network in Korea. Since then, new road constructions have been declined due to the economic downturn. Table 1 shows the sections selected from the five routes: route 20 (Iksan–Pohang Expressway), route 30 (Dangjin–Sangju Expressway), route 40 (Pyeongtaek–Jecheon Expressway), route 45 (Jungbu-inland Expressway), and route 60 (Seoul–Yangyang Expressway). The total length of the selected sections was 122.9 km (89.5 km road-only sections, 16.4 km tunnels, and 16.9 km bridges) and

Table 1
Twelve road sections selected for materials-induced CO_2 estimation.

No.	Section	Road-only (m)	Tunnel (m)	Bridge (m)	Total (m)
1	Route 20 Zone 7	7,500	700	740	8,940
2	Route 30 Zone 1	7,740	0	380	8,120
3	Route 30 Zone 3	9,636	2402	2270	14,308
4	Route 40 Zone 2	5,627	0	2041	7,668
5	Route 40 Zone 7	4,718	0	1599	6,317
6	Route 45 Zone 7	5,800	3077	263	9,140
7	Route 45 Zone 8	6,820	1,232	1993	10,045
8	Route 45 Zone 9	7,254	3983	1180	12,417
9	Route 45 Zone 10	8,729	980	2196	11,905
10	Route 45 Zone 11	13,873	0	2077	15,950
11	Route 45 Zone 12	11,140	365	1932	13,437
12	Route 60 Zone 16	722	3718	240	4,680

Table 2
Main materials and CO_2 emission factors [22].

Item	Unit	Unit price in USD/KRW	Emission factor (kg-CO_2/unit)
Steel bar	Ton	54.1/65,000	3500
Cement	Ton	54.5/65,400	1049
Ready-mixed concrete and concrete	Ton	35.9/43,190	409
Aggregate	Ton	7.5/9,000	3
Asphalt	Ton	34.1/41,000	53

most of them were paved with plain cement concrete (i.e., no steel reinforcement). Some sections had no tunnels but bridges existed on all twelve sections. Most of tunnels (89%) were built with a single construction method named the New Australian Tunneling Method, indicating there were no significant changes or variables in materials used for building tunnels. However, various types of bridge types were introduced on those sections. Therefore, the emissions from bridges ware investigated with respect to bridge types such as SBG, RC, PSC, MSS, FCM+MSS, and ARCH. The emissions from tunnels and bridges have been quantified separately to evaluate their contributions to overall CO_2 emissions and have been compared to those from road-only sections.

Table 3
Basic materials and CO_2 emission factors.

Item	Unit	Unit price in USD/KRW	Emission factor (kg-CO_2/unit)
Renewable wood	Ton	0.5/604	866
Bolt and nut	Ton	0.8/1,000	2
Rivet	Ton	2.4/3,000	9
Gravel	Ton	5.6/7,000	3
Sand	Ton	6.4/8,000	3
Special plywood	Ton	6.4/8,000	6
Planks	Ton	11.6/14,000	8
Silica and silica rock	Ton	17.5/21,000	16
Regular cement	Ton	40.8/49,000	322
Blast furnace slag cement	Ton	42.5/51,000	335
Steel-use pig iron	Ton	98.3/118,000	3,164
White cement	Ton	108.3/130,000	859
Foundry pig iron	Ton	148.3/178,000	4,762
Asphalt	Ton	178.3/214,000	184
Refractory cement	Ton	203.3/244,000	593
High-strength rebar	Ton	236.6/284,000	3,466
Regular rebar	Ton	239.1/287,000	3,500
Section steel–regular steel	Ton	322.5/387,000	4,166
Timber–regular steel	Ton	326.6/392,000	4,333
Bar steel–regular steel	Ton	337.5/405,000	4,951
Timber–special steel	Ton	395.8/475,000	5,248
Bar steel–stainless steel	Ton	1,816.6/2,180,000	26,626
Zinc steel sheet	Ton	513.3/616,000	2,241
PC steel wire	Ton	520.8/625,000	2,335
Stone blade steel sheet	Ton	542.5/651,000	2,369
Zinc wire	Ton	543.3/652,000	2,439
Regular plywood	Ton	659.1/791,000	608
Thinner	Ton	781.6/938,000	1,502
Stainless steel wire	Ton	2,918.3/3502,000	13,089
Compressed wood	Ton	954.1/1145,000	1,641
Processed wood	Ton	1,003.7/1205,000	711

2.2. Types of construction materials

Construction materials largely consist of main and basic materials. The main materials are considered as fundamental components of all infrastructure and are normally consumed in a large quantity. According to the standard cost estimate manual for construction developed by the Korea Society for the Construction Advancement (KSCA), there are five main materials: steel bar, cement, ready-mixed concrete and concrete, aggregate and asphalt. Table 2 shows the unit price and emission factor of those. The emission factor is defined as the amount of emissions per unit consumption of materials. Different materials have different emission factors depending on how they are produced. Among the main materials, steel bar has the highest emission factor, followed by cement concrete, ready-mixed concrete and concrete, asphalt and aggregate. This implies that steel structures can be more detrimental to the environment than cement concrete structures for the same amount of materials consumed. Other than main materials, most of construction materials can be categorized into basic materials. Table 3 summarizes thirty one basic materials defined by the Korea Ministry of Construction and Transportation (MOCT). Bar steel–stainless steel has the highest emission factor followed by stainless steel wire. It appears that steel products are generally more expensive and induces more emissions than wood and cement products. The determination of emission factors involves scientific experiments and analyses, and more detailed information on that can be found elsewhere [22,23].

2.3. Overall and unit emissions

First, overall emissions induced by the uses of main and basic materials were quantified with emission factors multiplied by the amounts of materials used for building each road section. These overall emissions were then converted into emission per meter (i.e., unit emission) using the section length. In this study, these unit emissions have been used to estimate total emissions that might have been released and accumulated on all types of roads in Korea such as expressways, national highways and local roads up to the year 2007. For basic materials whose emission factors were not available in the LCI database but used for the road constructions, a simple linear relation between the unit price and emission factor has been developed with data shown in Table 3 because emission factors were almost proportional to unit prices except for a few items. This linear model (Eq. (1)) seems reasonable as two variables are highly correlated (R^2=0.8704). It is also justifiable because the amount of emitting CO_2 gases normally becomes

Table 4
CO_2 emissions from main materials (road-only sections).

No.	Unit emission (tCO_2/m)	Overall emission (tCO_2)	Main materials ($kgCO_2$)				
			Steel bar	Cement	Concrete[a]	Aggregate	Asphalt
1	4	32,875	2,829,498	28,917,038	16,848	1,111,608	0
2	7	52,712	10,292,569	42,143,724	49,171	226,906	0
3	7	64,816	3,788,523	26,364,198	32,375,060	1,390,903	897,463
4	13	72,471	2,959,352	29,161,817	38,049,211	1,708,238	592,461
5	16	77,208	3,720,136	24,167,721	48,094,006	537,076	689,212
6	5	29,871	3,245,057	24,164,845	832,295	1,037,572	591,149
7	5	32,487	3,605,931	27,654,817	34,348	1,191,805	0
8	7	50,709	2,214,031	22,729,278	23,523,507	879,828	1452,165
9	11	92,116	11,243,901	38,155,615	40,890,476	1,826,268	0
10	5	62,730	9,975,952	50,663,949	28,139	2,062,235	0
11	5	60,353	9,074,933	49,078,352	577,314	1,621,990	0
12	57	40,810	1,839,961	15,267,885	21,780,980	469,007	1452,165
Total	–	669,158	64,699,842	378,469,239	206,251,355	14,063,436	5674,615

[a] Ready-mixed concrete and concrete.

Table 5
CO_2 emissions from main materials (tunnels).

No.	Unit emission (tCO_2/m)	Overall emission (tCO_2)	Main materials ($kgCO_2$)				
			Steel bar	Cement	Concrete	Aggregate	Asphalt
1	43	30,086	2,990,393	15,532,409	13,563,498	–	–
2	–	–	–	–	–	–	–
3	19	45,363	11,778,925	32,679,171	466,437	438,712	–
4	–	–	–	–	–	–	–
5	–	–	–	–	–	–	–
6	34	105,603	7,726,747	48,971,203	48,236,613	668,178	–
7	29	36,039	1,708,760	16,926,672	17,165,971	237,543	–
8	30	118,286	8,210,496	58,507,414	50,905,797	662,355	–
9	21	20,766	2,557,597	17,990,273	–	218,002	–
10	–	11,596	3,255,399	4,581,598	3,106,854	652,336	–
11	23	8,542	2,037,336	6,420,114	–	84,307	–
12	30	110,806	6,932,345	52,265,427	50,905,797	702,305	–
Total	–	487,087	47,197,997	253,874,282	184,350,968	3663,738	–

Table 6
CO_2 emissions from main materials (bridges).

No.	Unit emission (tCO_2/m)	Overall emission (tCO_2)	Main materials ($kgCO_2$)				
			Steel bar	Cement	Concrete	Aggregate	Asphalt
1	126	93,025	30,931,957	24,474,126	37,266,668	352,157	–
2	73	27,906	9,366,371	10,746,640	7,637,266	155,450	–
3	102	230,624	95,884,446	74,840,732	59,008,854	899,805	–
4	354	721,874	604,152,000	58,870,334	57,629412	1221,950	–
5	62	98,673	24,851,908	25,665,961	47,837,448	317,671	–
6	58	15,309	5,686,902	4,934,054	4,623,209	65,330	–
7	94	186,516	49,360,364	66,555,690	70,113,836	486,604	–
8	117	138,383	42,817,229	34,115,162	60,994,937	456,161	–
9	97	213,723	58,123,569	59,936,838	94,958,402	704,644	–
10	76	158,334	62,285,318	48,004,980	47,988,141	55,080	–
11	69	132,809	54,948,079	48,256,064	29,126,152	478,939	–
12	63	15,225	4,535,367	5,339,672	5,277,893	72,195	–
Total	–	2032,402	1042,943,507	461,740,254	522,462,217	5255,985	–

greater as the prices increase due to more energy and complicated treatments (chemical and/or physical) needed for manufacturing materials. Using the Eq. (1), one can now determine either emission factors or overall emissions.

$$E = 0.0038C + 72.362 \quad (1)$$

where

E = CO_2 emission factor (kg-CO_2/ton)
C = Unit price of construction materials (KRW/ton)

3. Results

3.1. CO_2 emissions from main materials

3.1.1. Road-only sections

Table 4 summarizes the emissions from road-only sections due to the use of main materials. Construction reports revealed all sections selected in this study were paved with plain cement concrete. Asphalt has been used in some sections mostly for base course and shoulder constructions. The total overall emissions came to 669,158 tCO_2. Of these emissions, 64,699,842 $kgCO_2$ were from steel bar, 378,469,239 $kgCO_2$ from cement, 206,251,355 $kgCO_2$ from ready-mix concrete and concrete, 12,237,168 $kgCO_2$ from aggregate and 5674,615 $kgCO_2$ from asphalt. Both cement (57%) and ready-mix concrete and concrete (31%) were the major CO_2 gas emitters. The emissions from steel bar were much less than those from cement and concrete even though emission factor of steel bar was much greater than those. In addition, overall emission was not proportional to the length of section since it has been affected by various emission factors and different amount of materials used. The section 12 had the highest unit emission (57 tCO_2/m) but overall emission was the lowest because the section length was the shortest. On average unit emission was about 7.4 tCO_2/m.

3.1.2. Tunnels

For the same sections, a total of 487,087 tCO_2 gases were resulted from main materials used for tunnel constructions as presented in Table 5. Since there were no tunnels on the (road) sections 2, 4, 5, and 10, no emissions were reported from those. Also, no emissions were induced from the asphalt because tunnels were paved with cement concrete in all cases. Of the total emissions, 47,197,997 $kgCO_2$ gases were generated from steel bar, 251,874,282 $kgCO_2$ from cement, 184,350,968 $kgCO_2$ from ready-mix concrete and concrete, and 3663,738 $kgCO_2$ from aggregate. It is clearly seen that most of the emissions were from the uses of cement (52%), ready-mix concrete and concrete (38%). Unit emissions of tunnels were larger than those of road-only sections because the uses of large amounts of high emission materials (e.g., cement and concrete). The average unit emission for tunnels (29.6 tCO_2/m) was almost four times larger than that for road-only sections.

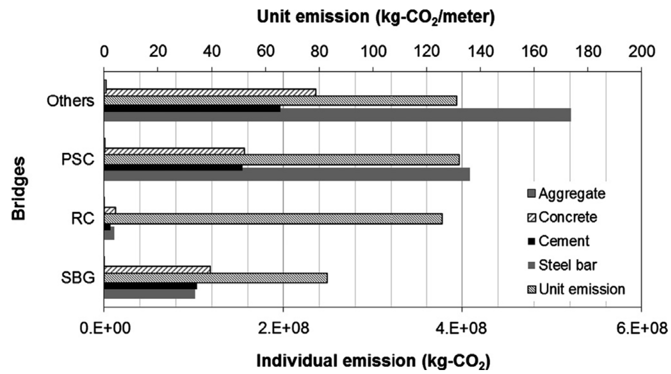

Fig. 2. CO_2 emissions with respect to bridge types.

Table 7
Lane composition for expressways in Korea as of 2007.

Type		Overall (km)	Ratio (%)	Road-only (km)	Tunnel (km)	Bridge (km)
Length (km)	2 lane road	155	5	100	15	40
	4 lane road	2402	71	1551	225	626
	6 lane road	407	12	263	38	106
	8 lane road	403	12	260	38	105
	Total	3367	100	2174	315	878

Table 8
Lane composition for national highways in Korea as of 2007.

Type		Overall (km)	Ratio (%)	Road-only (km)	Tunnel (km)	Bridge (km)
Length (km)	2 lane road	7,126	53	6,743	92	291
	4 lane road	5,575	41	5,276	72	228
	6 lane road	718	0.1	679	9	29
	8 lane road	40	0.007	38	1	2
	10 lane road	8	0.002	8	0	0
	Total	13,467	100	12,744	173	550

Table 9
Lane composition for local roads in Korea as of 2007.

Type		Subtotal	Ratio (%)	Road-only	Tunnel	Bridge
Length (km)	2 lane road	13,297	91	13,034	29	235
	4 lane road	1,096	8	1,074	2	19
	6 lane road	150	0.01	147	0	3
	8 lane road	107	0.007	105	0	2
	10 lane road	1	0.00007	1	0	0
	Total	14,651	100	14,361	32	258

3.1.3. Bridges

Table 6 summarizes the overall and unit emissions from bridges due to the uses of main materials. The average unit emission (120 tCO_2/m) of bridges was nine times larger than that of road-only sections and approximately six times larger than that of tunnels. The steel bar was one of significant contributors to the emissions (1042,943,507 $kgCO_2$), followed by cement (461,740,254 $kgCO_2$), ready-mix concrete and concrete (522,462,217 $kgCO_2$), and aggregate (5255,985 $kgCO_2$). To understand the effect of bridge types on the emissions, bridges were categorized into four groups: SBG, RC, PSC, and others. MSS, FCM+MSS, and ARCH bridges were consolidated into the others group. In each bridge type, the unit emission was estimated based on the types and quantities of materials needed, and then total materials-induced emission was obtained by multiplying the unit emission with total bridge lengths. As Fig. 2 illustrates, SBG bridges had the least unit emission (82.9 tCO_2/m), whereas PSC bridges had a relatively large unit emission (132.1 tCO_2/m). More than half of the total CO_2 emissions were produced by SBG, RC and PSC bridges as these have been the most popular bridge types on expressways for their constructability, performance and maintenance.

3.2. CO_2 from basic materials

For some basic materials whose emission factors are not listed in Table 3, Eq. (1) was utilized. In this study, overall emissions from those materials were directly estimated for each road section with the total costs (unit cost multiplied by the amount used). As a result, overall emission came to 33,389 tCO_2 on the route 30 in zone 1, 74,425 tCO_2 on the route 40 in zone 7, and 70,681 tCO_2 on the route 60 in zone 16. Average unit emission from basic materials turned out 9.337 tCO_2/m. This is much less than those estimated for tunnels and bridges due to the use of main materials.

3.3. Estimations of materials-induced emissions for all road types

Based on the unit emissions obtained so far, the materials-induced CO_2 gases were estimated for all types of roads up to the year 2007. For simplicity, roads were categorized into three classes: expressway, national highway and local roads. As Tables 7—9 show the total lengths of expressways, national highways, and local roads in Korea were 3367, 13,467, and 14,651 km, respectively. Most of roads were built with two lanes except for expressways (71% of expressways were built with four lanes). Tunnels and bridges on expressways were much longer than tunnels and bridges on national highways and local roads. About 35% of expressways were composed of tunnels and bridges, whereas slightly over 5% of national highways and 2% of local roads were built with tunnels and bridges.

First, emissions resulting from all expressways were estimated with respect to the number of lanes. Fig. 3 illustrates the contributions from different number of lanes. Only emissions from main materials were considered in this estimation. It was found that about 151,631,376 tCO_2 were released in total and most of them were from four-lane roads. It appeared that during the construction of one kilometer of expressway main materials have induced about 9729 tCO_2 per lane. Bridges were the largest CO_2 emitters (122,099,717 tCO_2), followed by road-only sections (18,743,467 tCO_2) and tunnels (10,788,193 tCO_2). Fig. 4 displays

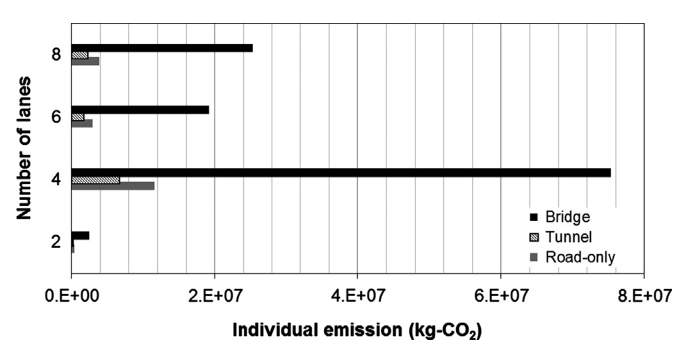

Fig. 3. CO_2 emissions with respect to the number of lanes on expressways due to the uses of main materials.

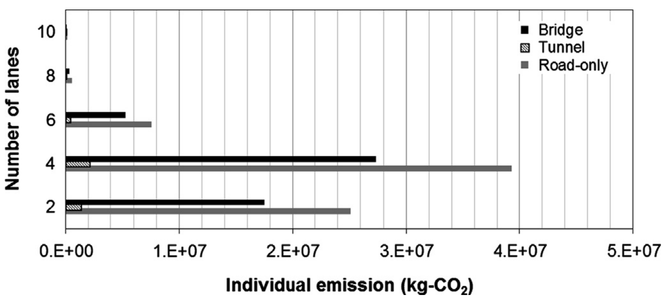

Fig. 4. CO_2 emissions with respect to the number of lanes on national highways due to the uses of main materials.

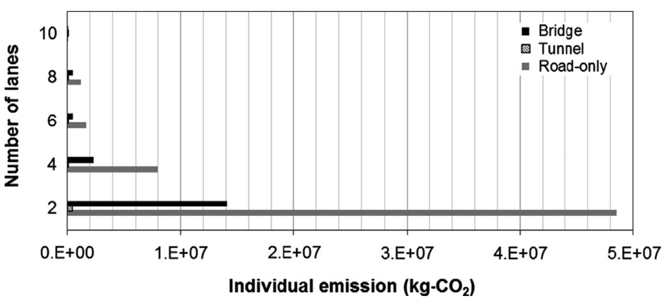

Fig. 5. CO_2 emissions with respect to the number of lanes on local roads due to the uses of main materials.

Table 10
Road construction plan from 2009 to 2020.

Year	Expressway		National road	
	Cumulative (km)	Individual (km)	Cumulative (km)	Individual (km)
2009	3561	–	14,280	–
2010	3753	192	14,299	19
2011	3945	192	14,318	19
2012	4137	192	14,336	18
2013	4329	192	14,355	19
2014	4521	192	14,374	19
2015	4678	157	14,389	15
2016	4835	157	14,405	16
2017	5148	156	14,435	15
2018	5305	157	14,451	16
2019	5462	157	14,466	15
2020	5619	157	14,481	15

the emissions from main materials used for the construction of national highways. The total CO_2 emissions turned out 127,211,339 tCO_2 (72,725,793 tCO_2 from road-only Section, 3, 921,993 tCO_2 from tunnels and 50,563,552 tCO_2 from bridges). Although the total length of national highways was almost four times longer than that of expressways, approximately 20% more CO_2 gases were generated from expressway constructions simply because tunnels and bridges built on the national highways were shorter than those on expressways. Approximately, 3085 tCO_2/lane/km were estimated for national highways. Fig. 5 shows the results for local roads. About 91% of the CO_2 emissions were from two-lane roads. Of the total emissions, 59,395,840 tCO_2 were from road-only sections, 529,167 tCO_2 from tunnels, and 17,351,773 tCO_2 from bridges. For local roads, about 2379 tCO_2/lane/km were calculated approximately. Given the estimations thus far, it can be said that about 356,119,495 tCO_2 might have been released from expressways, national highways and local roads due to the uses of main materials. The cumulative emissions became slightly less than 300 million tCO_2 (293,975,445 tCO_2) for all road types (31,437,679 tCO_2 from expressways, 125,741,379 tCO_2 from national highways and 136,796,387 tCO_2 from local roads). Therefore, 650,094,940 tCO_2 were determined as the total materials-induced emissions for all road types as of 2007.

3.4. Prediction of CO_2 emissions

According to road construction plans in Korea [24], one hundreds ninety two kilometer long expressways are going to be constructed every year between 2009 and 2014. For the same period 19 km long national roads will be newly built every year. From 2015 to 2020, it is expected that 157 km of expressways and 15 km of national roads will be constructed each year as listed in Table 10. It clear that similar plan has been set up for local road constructions, but relevant data were not available at the time of this study. Although this plan could be changed with public demands for new constructions and allocation of national budgets, average annual CO_2 emissions have been predicted for these two periods according to the plan. It should be noted that the technical progress of equipment and materials used in road construction was not considered to predict the average annual CO_2 emissions in this study.

Table 11 shows average annual CO_2 emissions due to expressway and national road constructions. For the first period (2009–2014), most of emissions (90%) would be from expressways due to the use of main materials. Similarly, 91% of emissions would be from expressways for the period 2. From the period 1 to period 2, average annual emissions would be reduced by 18% simply due to the reduction of road length.

4. Summary and conclusions

This study has attempted to quantify the CO_2 emissions due to materials used for road construction in Korea. Some of key findings drawn from this study are presented below:

- Due to the uses of main materials, average unit emissions were 7451 tCO_2/km from road-only sections, 29,598 tCO_2/km from tunnels, and 120,179 tCO_2/km from bridges. Average unit emissions for roads including tunnels and bridges were about 11,311 tCO_2/km.
- Bridges had the highest unit emission over 16 times larger than that for road-only sections. Steel bar was the biggest contributor to the emissions from bridges, whereas most of materials-induced emissions on tunnels and road-only sections were generated by the use of cement and ready-mix concrete and concrete.
- It was found that the PSC beam caused the highest level of materials-induced emissions (131,120 tCO_2/km). It appeared that the steel box girder was the most environmentally friendly.
- In each kilometer of roads, expressways have contributed to the highest emissions per lane, followed by national highways and local roads.
- For the construction of four-lane cement-concrete roads, average unit emission due to basic materials turned out 9337 tCO_2/km. As the number of lanes increased from 2 to 4, the amount of CO_2 emissions became more than doubled.
- On average, it was predicted that a total of 4365,526 tCO_2 should be released every year for a 2009–2014 period and 3558,627 tCO_2 for a 2015–2020 period due to the construction of expressways and national roads in Korea. Majority of these emissions was caused by the use of main materials.

As practiced in many road maintenance sites, recycling cement may help us to reduce the emissions to some degree. However, it is

Table 11
Average annual CO_2 emissions (2009–2020).

Period	Type	Main material		Basic material		Total (tCO_2)
		Expressway	Nat'l road	Expressway	Nat'l road	
Period 1 (2009–2014)	Length (km)	192	19	192	19	
	tCO_2	2171,712	214,909	1792,704	177,403	4356,728
Period 2 (2015–2020)	Length (km)	157	15	157	15	
	tCO_2	1775,827	169,665	1465,909	140,055	3551,456

the time to start considering a new way of producing construction materials that are environmentally safe and reusable in order to curb the GHG emissions proactively.

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